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THE EFFECT OF PERIODIC OVERLOADS ON FLIGHT-BY-FLIGHT FATIGUE CRACK GROWTH RATES

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The life prediction of aerospace structures subjected to service loading conditions can be complex and expensive. Fortunately, many flight-by-flight loadings can be analyzed as constant amplitude loading if the variability in crack growth rate is low. A test program was designed such that the stress intensity factor (K_{max}) was held constant by uniformly reducing the load as the fatigue crack grew. With a constant K_{max}, the crack growth rate remains constant throughout the life of the test. The baseline fatigue crack growth rate

Block 20 (Continued)

variability was established for the 7075-T6 center-cracked panels under a flight-by-flight load history. The effect of introducing overloads to the baseline flight history on the crack growth rate variability was reported. The results indicate that the delay region for the applied 114% overload was predicted by Irwin's plastic zone model and was equal to 0.0382 inches which was equal to 225 flights. The delay behavior was consistent for the several overload conditions that were studied. When the occurrence of overload increased, the fatigue crack growth rate decreased. The standard error of estimate remained relatively constant, suggesting that a block approach to life prediction is feasible for flight-by-flight load history.

FOREWORD

This report describes an in-house effort conducted under Project 2401, "Structures and Dynamics," Task 240101, "Structural Integrity for Military Aerospace Vehicles," Work Unit 24010109, "Life Analysis and Design Methods for Aerospace Structure."

This work was performed for the Structural Integrity Branch, Structures and Dynamics Division, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories (AFWAL/FIBEC), Wright-Patterson Air Force Base, Ohio, 45433. The research was conducted under the direction of Ms. Margery A. Dean from July 1977 to May 1979.

The author wishes to recognize Messrs. Harold Stalnaker, Jack Smith, Larry Bates, and Richard Kliesmit for their contributions in the accomplishment of the experimental phases of the study. In addition, the efforts of Mr. Joe Fletcher for drafting the figures and Dr. Joseph Gallagher for his early guidance were very much appreciated. Much appreciation is given to Ms. Elaine Willingham for typing the manuscript.

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LIST OF SYMBOLS

a	Crack length
a^*	Crack length affected by overload
a_o	Crack length at beginning of the increment
a_k	Total crack length at the end of an increment
Δa	Crack growth during the increment
Δa_{delay}	The change in crack length affected by an overload
Δa_{ss}	The constant (steady-state) change in crack length, unaffected by overloads in the flight
α	The constant in Irwin's plastic zone equation $\alpha = 2$ for plane stress, $\alpha = 3$ for plane strain
da/dN	Crack growth rate; change in crack length per cycle
da/dF_{delay}	The slower crack growth rate caused by an overload
da/dF_{ss}	The baseline crack growth rate, termed steady-state
F	Flights
F^*	The number of flights with overload - affected crack growth
K	The stress intensity factor (SIF)
K_{max}	The maximum stress intensity factor in the flight
K_{min}^{eff}	The minimum effective stress intensity factor in the cycle
K_{max}^{eff}	The maximum effective stress intensity factor in the cycle
$\overline{K}^{eff}$	The constant amplitude equivalent stress intensity factor frequently calculated from the rms of the stress history
ΔK	The stress intensity factor range
ΔK^{eff}	Effective stress intensity factor range for variable amplitude loading
N	Number of cycles
N_F	The final number of cycles
R	The stress ratio, minimum stress in the cycle divided by the maximum stress in the cycles

LIST OF SYMBOLS (Concluded)

R^{eff}	Effective stress ratio for variable amplitude loading
$\bar{R}^{eff}$	The stress ratio of the constant-amplitude-equivalent stress history
r_y	The radius of Irwin's plastic zone
W	The specimen width

SECTION I

INTRODUCTION

Efficient and reliable crack growth rate prediction methods are important to the design of fracture critical aerospace structures. There are many crack growth rate equations which are available for predicting crack growth rates and lives based on constant amplitude stress histories (References 1-3). Over the past few years, these equations have been modified to account for variable amplitude loading by considering the effective stress intensity factor and effective stress ratio of the next cycle. The crack growth increments are generated cycle-by-cycle. Methods in common use account for the delay in crack growth associated with the application of a higher load added to the load history (References 4, 5). The crack growth increments are then calculated on a flight-by-flight basis. Barsom (Reference 6), Elber (Reference 7), and Gallagher (Reference 8) have investigated the use of constant-amplitude-equivalent models to make predictions for random loading more efficient. This approach is plausible because it was found that many common variable amplitude load histories generate constant-amplitude-type, crack growth rate behavior. Applied overloads are analyzed for this class of flight-by-flight histories by separating the history into two distinct blocks, the overload affected block and the constant-amplitude-equivalent block.

In this report, results of an experimental program to investigate the feasibility of such a block approach in a crack growth rate prediction scheme for flight-by-flight histories are presented. Baseline crack growth rate data were established under constant stress intensity factor (K_{max}) conditions. Overloads of 130 percent of the maximum repeating value in the stress history were added at various intervals to evaluate the nature of the delay caused by the overload by investigating the statistical nature of the slower crack growth and the recovered crack growth rate.

The objective of this study was to investigate the nature of the flight-by-flight fatigue crack growth (FCG) delay and its dependency on the prevalence of the overload. This study is relevant to the improvement of flight-by-flight FCG life predictions.

SECTION II

BACKGROUND

Early techniques for predicting crack growth under cyclic loading made use of direct integration of constant amplitude fatigue crack growth rate data on a discrete cycle-by-cycle load basis. The crack incrementation intervals were selected by the analyst or computed automatically using one of the available computer programs such as the one described in Reference 9. This incrementation scheme follows from the integration of the crack growth rate derived from constant amplitude data:

$$a_k = a_0 + \sum_{j=1}^{N} \Delta a_j \tag{1}$$

where N is the number of cycles corresponding to some intermediate crack length a_k. The a_o is the crack length at the beginning of the increment and Δa is the crack growth during the interval. The next cycle produces crack growth which can be expressed in terms of the stress intensity factor (ΔK) and the stress ratio (R); such that:

$$\Delta a_{N+1} = \frac{da}{dN}_{N+1} = f(\Delta K_{N+1}, R_{N+1}) \tag{2}$$

This approach is acceptable for many applications but is highly conservative for some variable amplitude load histories. This is because load-interaction effects due to overloads and underloads are not accounted for. Overloads occurring in a variable amplitude history have the effect of retarding the succeeding Δa over a given crack length. Therefore, other techniques have since been developed which do account for such crack growth rate behavior. A commonly used retardation model is the Willenborg model (Reference 5).

The Willenborg model (Reference 5) accounts for retardation by postulating a reduction in the applied stress due to residual stresses set up by the preceding overload. In conjunction with constant amplitude

crack growth-rate data, the effective stress-intensity factor ΔK^{eff} is used to generate the Δa for the next cycle:

$$\Delta a_{N+1} = \frac{da}{dN}_{N+1} = f(\Delta K^{eff}_{N+1}, R^{eff}_{N+1}) \tag{3}$$

where R^{eff} is the effective stress ratio, based on K_{min}^{eff} and K_{max}^{eff} for the next cycle. The effective stress intensity factor takes into account the high-to-low load interaction effects. The residual stress is assumed to decay over a crack length equal to Irwin's plastic zone, r_y, created by the overload;

where: $r_y = \frac{1}{\alpha\pi}\left(\frac{K_{OL}}{\sigma_{ys}}\right)^2$,

K_{OL} = the stress intensity factor of the overload,

σ_{ys} = the yield stress of the material,

α = 2 for plane stress,

α = 6 for plane strain.

This model, although satisfactory for random loading, is not satisfactory for flight-by-flight loading because such spectra maximize the influence of high loads, which makes the prediction highly conservative for low to high sequences.

Gallagher (Reference 8) and others have investigated a block approach for predicting flight-by-flight crack growth rates. It has been shown that for several variable amplitude loading cases, crack growth behavior is similar to constant amplitude loading crack growth behavior. Examples are transport/bomber design spectra which are composed of "short" repeating flights. As described by Gallagher, a block approach to crack growth prediction is much more efficient than the cycle-by-cycle approach with approximately the same accuracy for qualifying stress histories. Here, the crack length is calculated by a method equivalent to Equation 1 for constant amplitude histories:

$$a_k = a_0 + \sum_{j=1}^{N_F} \Delta a_j \tag{4}$$

where N_F is the number of flights corresponding to the crack length a_k. The incremental crack length is calculated in a manner similar to Equation 3:

$$\Delta a_{\substack{j+1\\eff}} = \frac{da}{dF_{j+1}} = f(\Delta \overline{K}^{eff}_{j+1}, \overline{R}^{eff}_{j+1}) \qquad (5)$$

where $\overline{K}^{eff}$ is the constant-amplitude-equivalent stress intensity factor, and $\overline{R}^{eff}$ is the corresponding stress ratio. A common approach is to compute $\overline{K}^{eff}$ from the rms stress level (References 6, 8) of the stress history. $\frac{da}{dF_{j+1}}$ equals the crack growth rate for the j^{th} flight. In this report, an extension or combination of the above methods is considered for more severe flight-by-flight loadings by investigating the crack growth rate data generated by adding periodic overloads to the flight history.

SECTION III

ANALYTICAL APPROACH

As a logical progression from the approaches mentioned previously, the following is suggested. The crack length calculation for the flight-by-flight load history with high-to-low load interaction is composed of two parts, the overload affected block, Δa^*_{delay} and the steady-state-constant-amplitude-equivalent block, Δa_{ss}. The crack growth for a total block is:

$$\begin{aligned}\Delta a_{j+1} &= \Delta a^*_{delay} + \Delta a_{ss} \\ &= \frac{da}{dF}_{delay} \times \Delta F^* + \frac{da}{dF}_{ss} \times (\Delta F - \Delta F^*)\end{aligned} \tag{6}$$

where a* and F* are the crack length and flights, respectively, associated with the overload-affected crack growth as shown in Figure 1. The main assumption of crack growth prediction for flight-by-flight load history with randomly occurring overloads is that the delay caused by the overload is consistent and predictable. If it is, then the above approach should work for complex flight-by-flight predictions. In this study, it was important to find out if the Δa^*_{delay} was repeatable, and equal to r_y. It also had to be determined if the Δa_{ss} was constant or recoverable after the application of overloads. One method for determining if such load histories containing overloads are acceptable for block analysis is to compare the fatigue crack growth (FCGR) variability with that observed for the baseline FCGR.

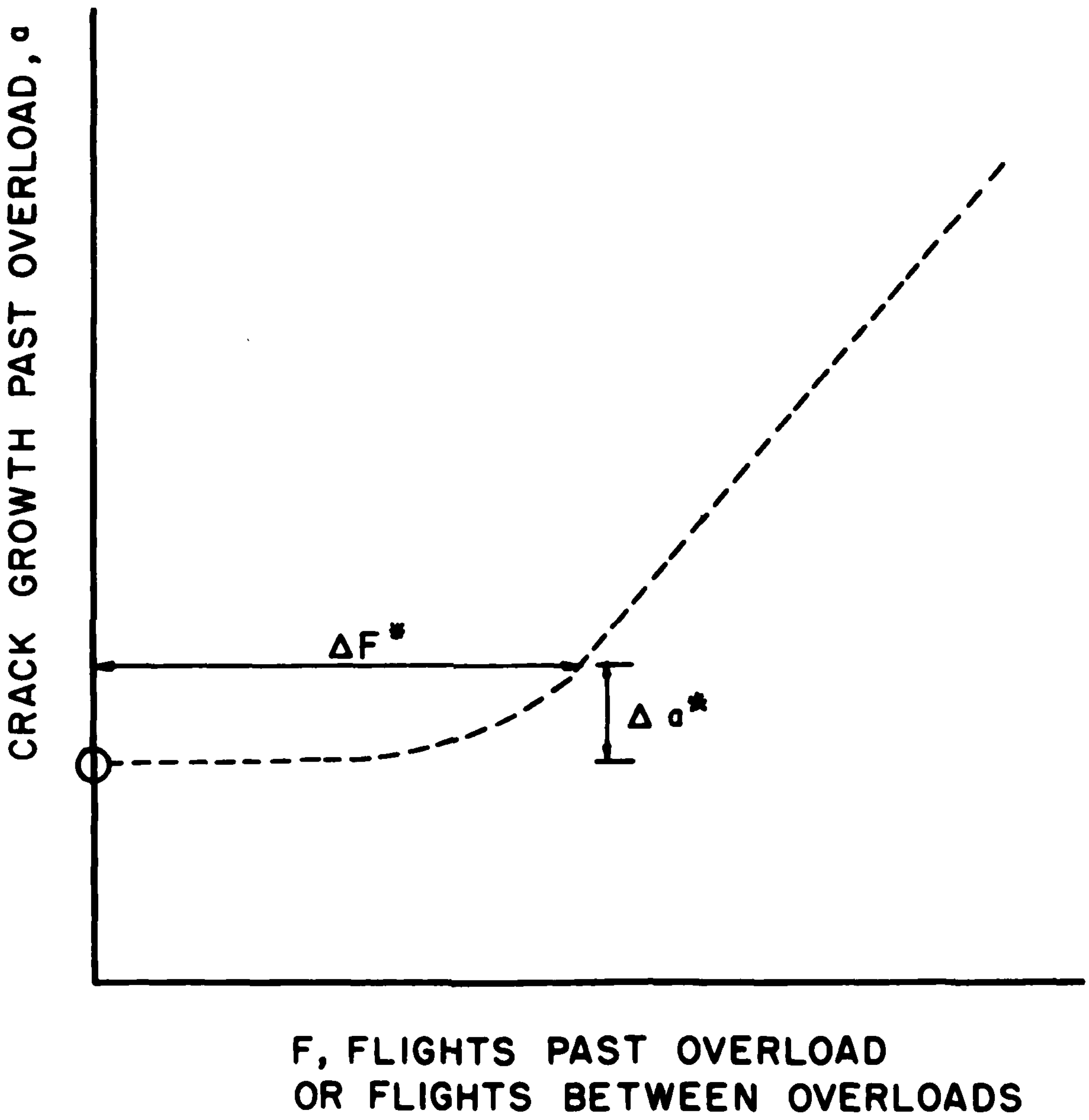

Figure 1. Schematic of Crack Length versus Flights Past Overload

SECTION IV

TEST METHODS AND PROCEDURES

1. MATERIAL, SPECIMEN GEOMETRY, AND TEST EQUIPMENT

A total of four 24-inch wide center-cracked panels fabricated from 0.182-inch thick 7075-T6 aluminum alloy were used, however, one panel failed early due to an electrical anomaly. The machined center notches for the panels were approximately 1.66 inches in length. The test equipment used included a 500-kip static, 250-kip dynamic capacity load frame under closed-loop servo-control used to apply the variable amplitude load history. The load levels and cycle shape were stored in a 4096 byte memory digital programmer and then fed to the load servocontrollers.

The applied test loads were monitored through an independent data system, and were maintained within 1% of the programmed value. The overloads were added separately.

2. LOAD HISTORIES

Two variations of a variable amplitude load history were used: 1) a basic flight-by-flight history, and 2) the basic history with overloads added periodically.

a. Basic Load History

The basic variable amplitude load history used in this investigation is shown in Figure 2. This history represents a single mission derived from the 135,000 cycle (per lifetime) bomber design load history described in (References 10, 11). There are 57 separate load levels and 123 cycles of load in the stress history given in Figure 2. The load levels are given in percent of the largest level experienced in the design-load history; note that the largest level in the repeating flight is 88 percent of the largest level in the design-load history. To avoid buckling the panels, the negative loads in the bomber mission were clipped to a zero load level as described by Figure 2. Dill and Saff

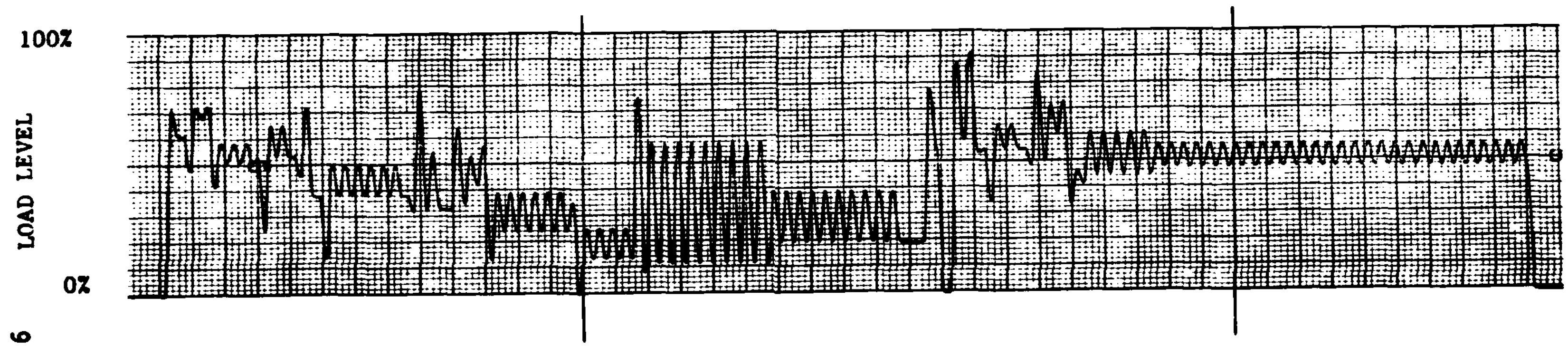

Figure 2. The Applied Flight History

(Reference 12) reported that clipping compression loads of less than -30% of the design limit stress to 0% had less than 10% effect on crack growth life.

b. Stress-Intensity Factor (SIF) Histories

The baseline FCG data were generated using the SIF history based on the variable amplitude loads defined in Figure 2. The basic history was based on a maximum SIF of 30 ksi$\sqrt{\text{in.}}$ Fifteen of the repeating flights were programmed as a block on the 4096 byte memory digital computer. A single overload was applied before every 1, 3, 12, 15, or 25 blocks of 15 flights depending on the test condition. The single load cycle was applied at a 114% load level (34.3 ksi$\sqrt{\text{in.}}$), which is equivalent to a 30% overload based on the highest load in the repeating flight.

3. CRACK GROWTH MEASUREMENT

For all test conditions, the crack length was measured each time a block of 15 flights had been applied. A binocular zoom microscope with a maximum magnification of 40X was used to make the measurement in conjunction with a Mylar scale calibrated in 0.005 inch increments attached to the specimen. The crack was measured on both sides of the notch and total crack length (2a) and flights (F) were tabulated.

4. STRESS-INTENSITY FACTOR (SIF) CONTROL PROCEDURES

The level of loading for this study was controlled so that the SIF coefficient (K/σ) was maintained at a constant level. Specifically, the load levels were proportionately reduced as the crack length increased according to the SIF finite-width secant formula suggested by Fedderson (Reference 13):

$$K = \sigma \left[\pi a \sec \frac{\pi a}{W}\right]^{1/2} \tag{7}$$

where W = specimen width. The stress (σ) used to describe test conditions was the 100% stress level associated with the stress history. The reported maximum stress-intensity factors (K_{max}) values were calculated based on the 100% level of stress. The level of SIF was controlled to within 1% of the desired conditions by ensuring that the total crack growth increment ($\Delta 2a$) did not exceed 0.050 inch prior to reducing the load level.

By keeping the SIF level constant, fatigue crack growth rate (FCGR) data were generated under conditions in which the normal crack growth driving parameter is fixed. By controlling the SIF, it was possible to accumulate the desired quantities of fatigue crack growth (FCG) data necessary to make statistical comparisons. Also, deviation from the baseline crack growth rate due to the applied overloads could be detected.

SECTION V

RESULTS AND DISCUSSION

1. DETERMINATION OF BASELINE BEHAVIOR

As an earlier part of this study, the variability of the baseline flight-by-flight FCGR data for constant SIF $K_{max} = 30\ ksi\sqrt{in.}$ was reported by Artley, et al. (Reference 14). No SIF gradient effect existed for this load history as the crack advanced through a particular panel. Therefore, the baseline steady-state FCGR behavior can be described as a function of a SIF parameter such as suggested by Equation 5. Such behavior was desired to investigate the effect of frequency of overloads on flight-by-flight FCGR. The FCGR for the four panels for the baseline, $K_{max} = 30\ ksi\sqrt{in.}$ condition, was found to range from 0.00464 in./block to 0.0101 in./block. The standard error of estimate, which is a measure of the variance from the mean, ranged from 1.61×10^{-5} to 1.16×10^{-4} in./block. The FCGR for Panel 2 was approximately 36% lower than the other three panels. This result highlights the need for the assessment of interspecimen variability, which may be substantially greater than intraspecimen variability.

2. EFFECT OF SINGLE OVERLOAD ON FCGR

Because the SIF coefficient (K/σ) was the control condition, different test histories could be run in any combination on a particular panel. A single overload of 114% of the maximum design stress (130% of the maximum repeating load level) in the load history was manually added to the baseline history. This test was performed to measure how many flights had to be applied before the growth rate recovered to the baseline rate and to investigate the amount of the delay.

As presented in Figure 3, the delayed region can be thought of as being composed of three parts: Region (I) an initial acceleration (brittle fracture), Region (II) delay, and Region (III) accelerated recovery, or "lost retardation." Past Region III, the FCGR returns to steady-state behavior. Similar trends have been reported by Bernard (Reference 15)

and Allison (Reference 16). The total overload affected area was found to occur over 15 blocks of 15 flights each for a total of 225 flights (Figure 3).

3. EFFECT OF PERIODIC OVERLOAD ON FCGR

Overloads of 114% of the maximum design load which were applied every 25 blocks (375 flights) produced crack growth behavior similar to that of the single overload case. The three regions of crack growth occurring in the plastic yield zone are present and occur in the period of 15 blocks following the overloads (Figure 4). After 15 blocks, the growth rate regains a steady-state rate of 0.00450 in./block, which is similar to the baseline rate for that panel (0.00464 in./block). The sample mean of the combined rate is less (0.00348 - 0.00374 in./block) because it contains the delayed region, Region II (Table 1).

The frequency of occurrence of the overload was increased so that the overload occurred while the crack tip was within the theoretical plastic zone created by the previous overload. The crack growth behavior was seen to contain the three regions over 15 blocks. No experimental measurements of plastic zone size were actually taken. This is apparent when looking at the groups of 15 blocks (225 flights) shown in Figure 5. Crack growth occurring after the overload exhibits behavior similar to that of the single overload (initial acceleration, retardation, and accelerated recovery). When the 114% overload is applied once every 12 blocks of flights, the region of acceleration and recovery which normally occurs in the last three blocks of the cycle is omitted, but the first two regions remain, as seen in Figure 6. As the periodicity of the overloads is increased to one application every 10 blocks, only the initial acceleration and part of the retardation regions remains in the cycle (Figure 7). For overloads repeated every third block, the growth is highly variable but cyclic in pattern because it contains almost equal portions of Region I and II growth (Figure 8). The overall rate may be established and used in an equivalent stress prediction scheme if intermediate crack growth measurements are omitted. For overloads applied once every block, the growth rate is highly variable and as

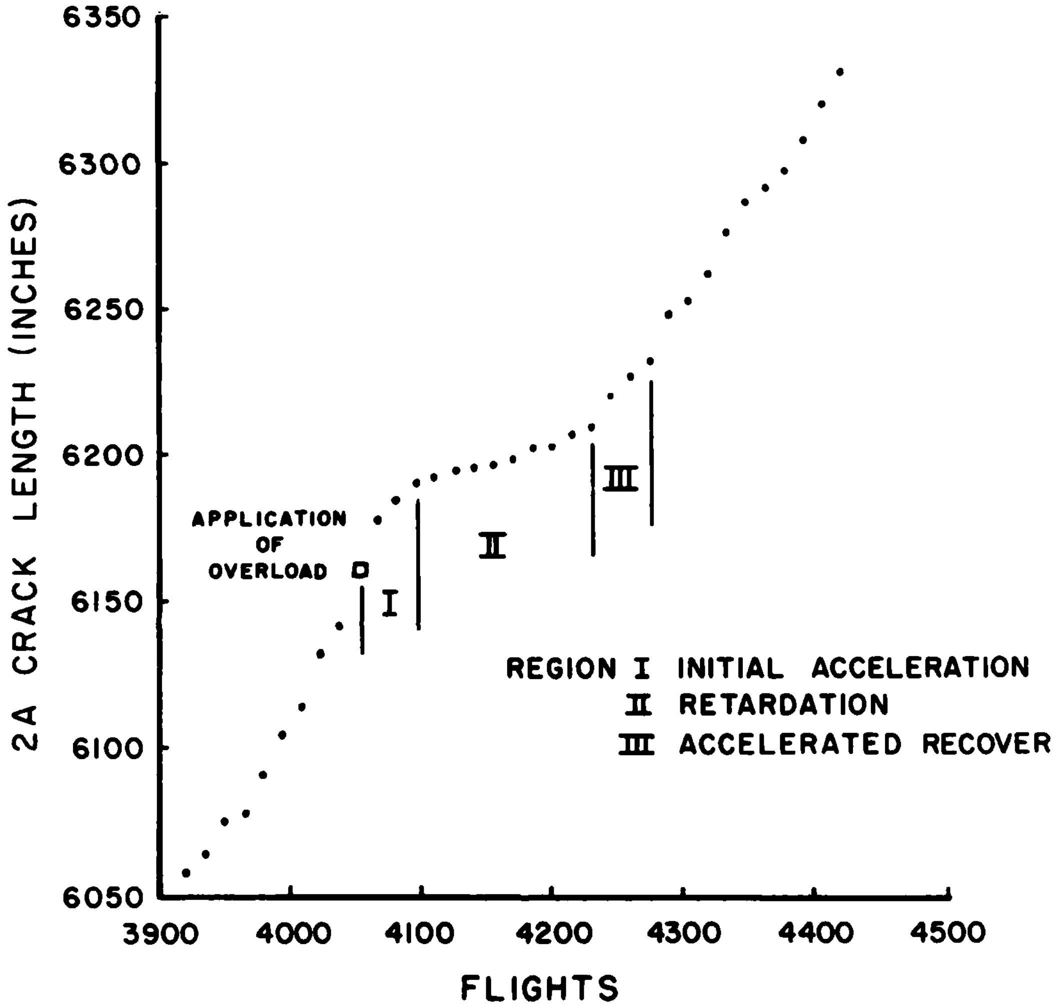

Figure 3. The Effect of a Single Overload in Crack Growth

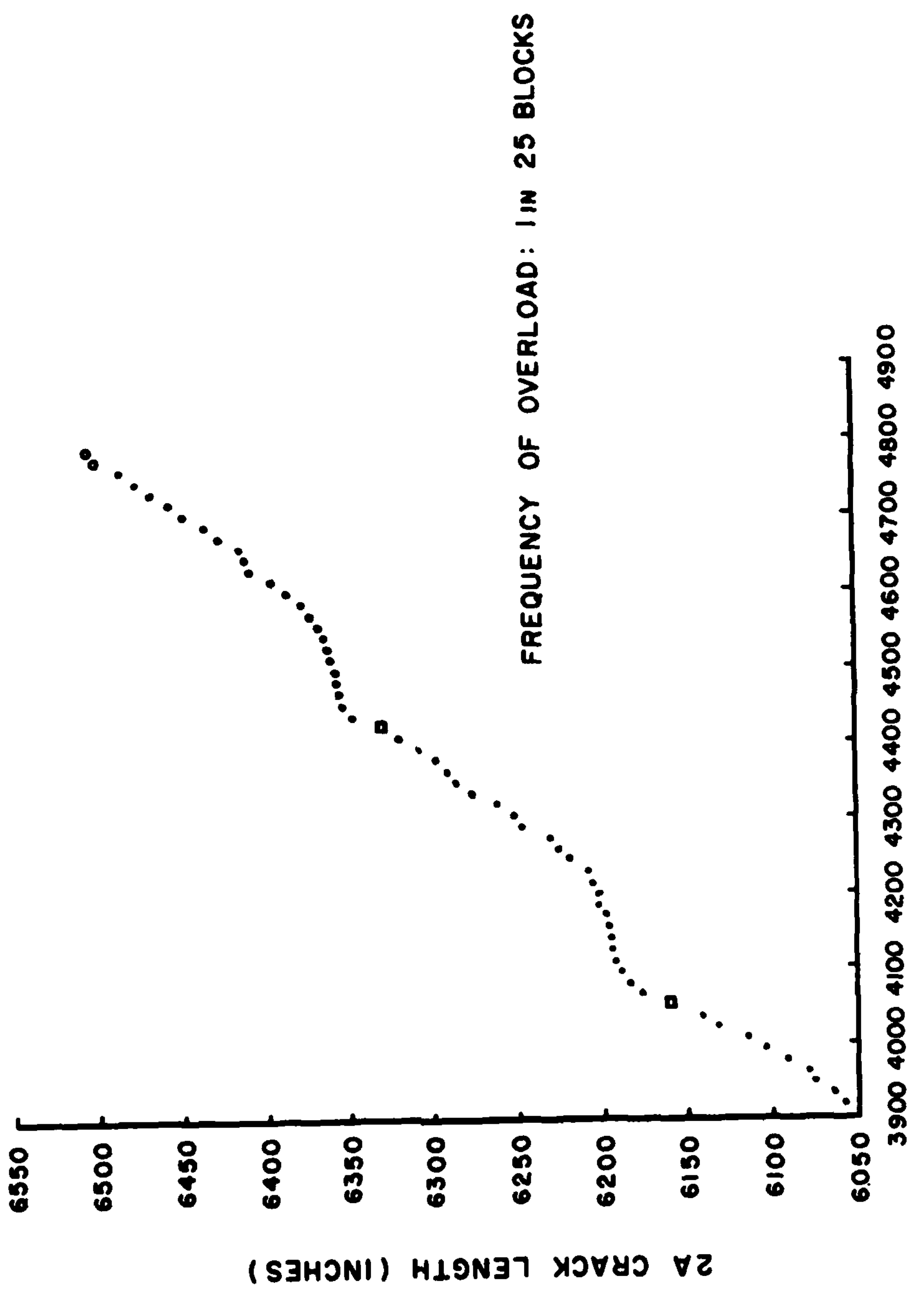

Figure 4. Constant Stress Intensity Factor (K) Crack Growth Affected by Overloads of One in Twenty-Five Blocks

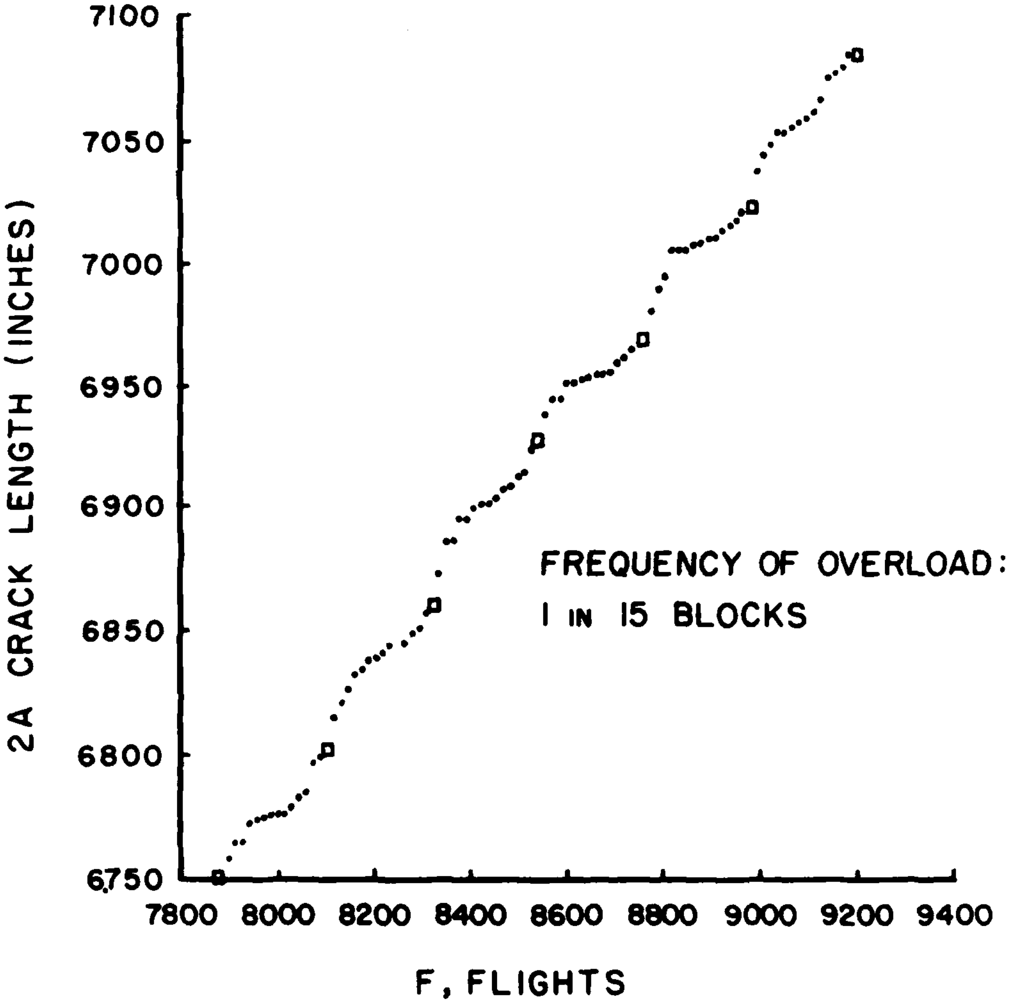

Figure 5. Constant K Crack Growth Affected by Overloads of One in Fifteen Blocks

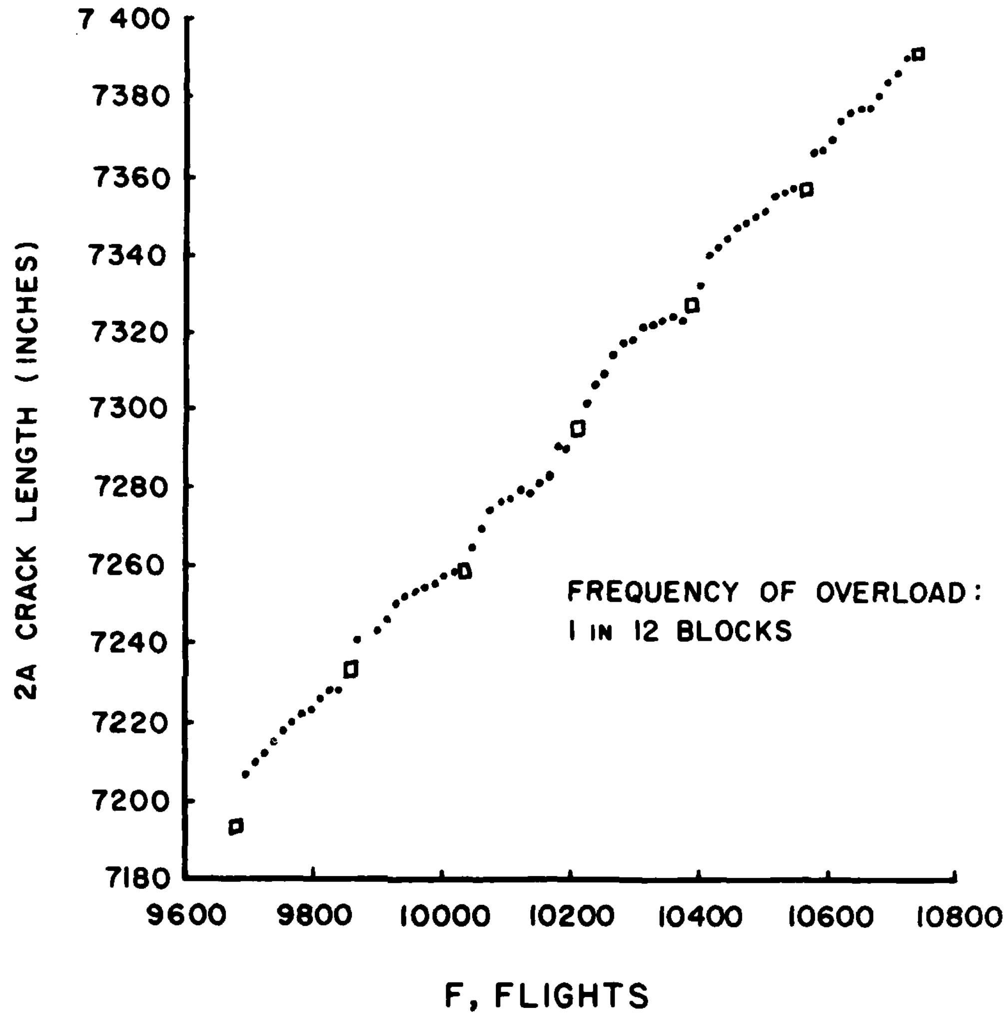

Figure 6. Constant K Crack Growth Affected by Overloads of One in Twelve Blocks

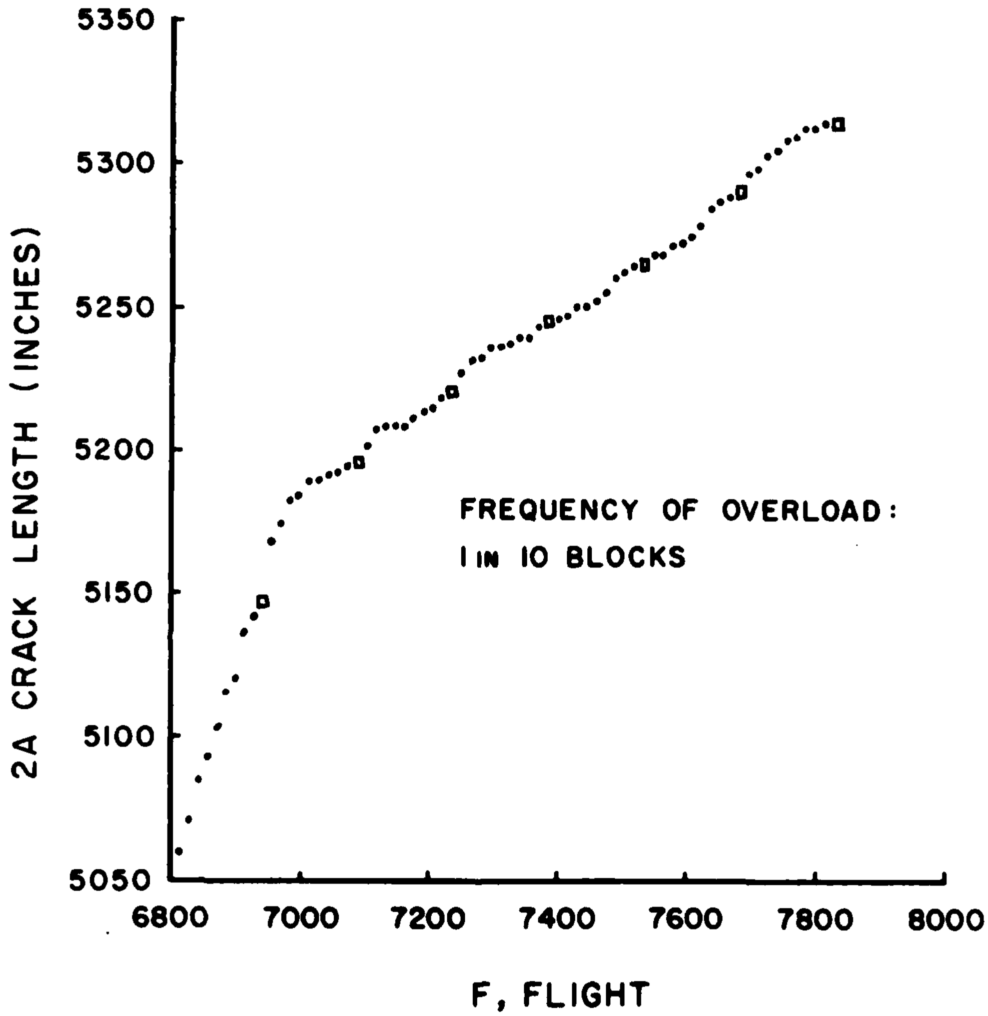

Figure 7. Constant K Crack Growth Affected by Overloads of One in Ten Blocks

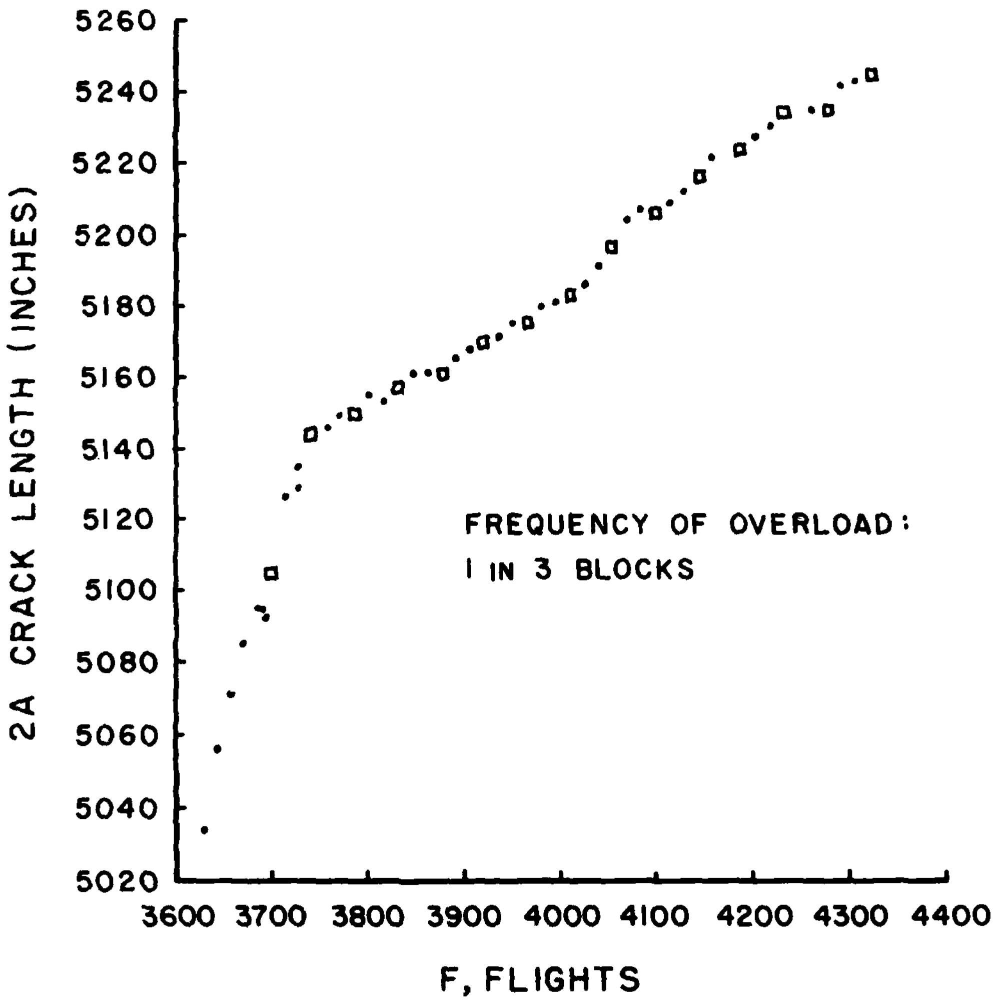

Figure 8. Constant K Crack Growth Affected by Overloads of One in Three Blocks

shown by the high standard errors of estimate in Table 1. The growth rates were more random in pattern than for the other overload conditions. So an equivalent K_{max} approach could not be used.

The growth rates for the various occurrences of overload are summarized in Table 1. The FCGR for the various load cases are highly variable. Because of the slower rate resulting from the application of the overloads, the FCG measurement interval is below that recommended by ASTM Standard Method of Test (Reference 17). Less variability would be recorded if the crack length measurement interval was increased by approximately five times the crack length measurement interval used here. Based on earlier studies, the mean FCGR will remain unaffected as the crack length measurement interval is increased (References 18, 19).

For overloads applied every three blocks the FCGR varied from 0.00119 to 0.00258 in./block at $K_{max} = 30\ ksi\sqrt{in.}$, while the FCGR for overloads applied every block ranged from 0.00156 to 0.00211 in./block. The growth rate for cracks subjected to overloads every 12 and 15 blocks is slightly faster because of a large initial acceleration and the inclusion of the region of "lost retardation." The FCGR is 0.00156 and 0.00177 in./block, respectively. Two effective stress regions can be found for overloads recurring after the crack tip has moved through the plastic zone created by the previous overload, i.e. (1/25), (1) a delayed region within the plastic zone where the FCGR is 0.0020 in./block and (2) a steady-state region of 0.0045 in./block beyond the overload-effected plastic zone, which is 0.0382 inches for overload of 114%.

TABLE 1

FATIGUE CRACK GROWTH RATES FOR VARIOUS OCCURRENCES OF OVERLOAD

Frequency of Overload	Panel	Sample Mean in/block	Standard Error of Estimate
Baseline	1	.00840	1.78×10^{-5}
"		.00775	1.16×10^{-4}
"		.00774	2.39×10^{-5}
	2	.00502	6.98×5^{-5}
		.00464	3.56×10^{-5}
	3	.00840	3.27×10^{-5}
	4	.0101	2.84×10^{-5}
		.00134	2.72×10^{-5}
		.00534	1.61×10^{-5}
1/1	1	.00159	5.07×10^{-5}
		.00211	9.68×10^{-5}
1/3	4	.00258	4.95×10^{-5}
		.00119	1.15×10^{-5}
1/12	4	.00156	7.58×10^{-6}
1/15	4	.00177	7.80×10^{-6}
1/25	2	.00374	1.10×10^{-4}
		.00348	5.03×10^{-5}
Single Overload	2	.00455	9.90×10^{-5}

SECTION VI

RECOMMENDATIONS

1. Baseline FCGR data were obtained from constant K_{max} tests. The rate remained constant as the crack length increased. The FCGR from additional levels of constant K_{max} tests should be investigated and compared to the data from the tests conducted at the 30 ksi$\sqrt{in.}$ level. Additional levels of overloads need to be applied to the flight history to verify that the delay behavior occurs within the calculated plastic zone.

2. When the occurrence of the overload was increased, the FCGR decreased. To determine if there is a limit to the decrease when a new, higher K_{max} level is established for the flight, overloads should be applied more often to verify that the FCGR will increase to a rate corresponding to the higher K_{max} level.

3. As shown by this study, each crack growth increment is dependent not only on the current load, but also on the previous load (up to a distance r_y) preceding it. The overloads applied in this study affected crack growth for up to 15 blocks. It is recommended that this dependency be acknowledged through statistical modeling of the load history. An example of such dependent modeling is a Markov chain. Life predictions carried out using a statistical modeling of the load history should be compared to experimental test results.

SECTION VII

CONCLUSIONS

1. The block approach to life prediction has potential as an analytical tool for components subjected to flight-by-flight load histories containing overloads.

2. The FCGR delay behavior was consistent for the several overload conditions that were studied.

3. For this flight-by-flight load history, the delay region due to overloads was predicted by Irwin's plastic zone which was equal to 0.0382 inches.

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